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HEAT BALANCE AND MEAN MERIDIONAL CIRCULATIONS IN THE POLAR STRATOSPHERE DURING THE SUDDEN WARMING OF JANUARY 1958

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ABSTRACT

In order to gain a greater understanding of the physical processes acting in the lower stratosphere during a major breakdown of the polar night vortex, a computation of the direction and magnitude of the mean meridional circulation is performed by employing a heat budget method. This computation reveals that the mean cell operates to produce rising motion over the polar regions before, during, and after the breakdown period. The calculations show that horizontal eddy heat flux provides the predominant mechanism for the large temperature increases observed over the polar cap during the time of the vortex breakdown. As a supplement to the above computation, mean vertical velocities were determined with respect to a curvilinear coordinate system oriented along a line of maximum circulation intensity at 50 mb. The result showed that the mean cell operates in the *direct* sense prior to the major breakdown when measured relative to this curvilinear system.

1. INTRODUCTION

With the advent of adequate meteorological data at higher levels, a great deal of attention has been shifted to the stratospheric circulation, particularly to the midwinter breakdown of the polar night vortex and the associated "sudden warming" phenomenon. A major breakdown of the polar night vortex is usually associated with an increasing departure of the circulation from zonal symmetry, finally leading to a complete reversal of the gradient of the zonal mean temperature north of the midlatitudes. This reversal occurs in a spectacular fashion, often requiring only a few days (fig. 1).

Because of the abrupt changes in circulation and mean thermal structure over such a short period of time, it is of interest to determine the mean meridional circulations over time scales compatible with the observed changes. Then, the relative contribution of the effect of the mean circulation upon the observed mean temperature changes can be determined.

Considerable controversy has existed in the literature concerning the sense and magnitude of the mean meridional circulation in this region. Some years ago, Brewer (1949) hypothesized that a mean meridional cell could exist in the stratosphere. He originally assumed that it would be a thermally direct circulation. However, the discovery of an indirect cell in the midlatitude troposphere suggested that the stratospheric circulation may also be dynamically driven and thus also operate in the indirect sense.

Earlier investigators on the problem of trace substance transport in the stratosphere concluded that a strong wintertime direct cell with sinking over the Pole is necessary to be compatible with the observed transports (Brewer, 1949; Dobson, 1956; Goldie, 1950; Palmer, 1959; Libby and Palmer, 1960).

More quantitative approaches to the mean cell problem have been extremely varied in nature. Tucker (1959) and Oort (1962) attempted direct measurements taken from the basic wind data. Oort's results suggest that a pronounced indirect cell is present in high latitudes of the polar night stratosphere. Haurwitz (1961) computed the mean meridional circulation to be expected from frictional considerations. His results suggest the existence of a direct cell in the stratosphere.

Other investigators (Kuo, 1956; Palmén, Riehl, and Vuorela, 1958; Dickinson, 1962; Teweles, 1963; Newell and Miller, 1965; Gilman, 1965; Holopainen, 1967; Vincent, 1968) have performed meridional cell computations based on the zonal momentum budget. This approach suggests that an indirect cell is operative in the polar night stratosphere.

Perry (1967) computed the mean cell for the polar night stratosphere using a zonal average of a solution to a simplified form of the vorticity equation. His results also point to an indirect circulation.

Another approach is to employ methods using the so-called "ω-equation." Miyakoda (1963) performed zonal averaging of ω values obtained from the balance ω-equation. Julian and Labitzke (1965) zonally averaged ω values determined from the quasi-geostrophic form. Vernekar (1967) solved the quasi-geostrophic ω-equation in a zonally averaged form. The results of Miyakoda (1963) and Julian and Labitzke (1965) also indicate the presence of the indirect cell.

Still others have used an approach invoking thermal considerations. Jensen (1961), Miyakoda (1963), and Reed, Wolfe, and Nishimoto (1963) all computed adiabatic vertical velocities, which were then zonally averaged. These results also show the indirect circulation. Of all the above studies, only Reed, Wolfe, and Nishimoto (1963) give results for the mean circulation over short

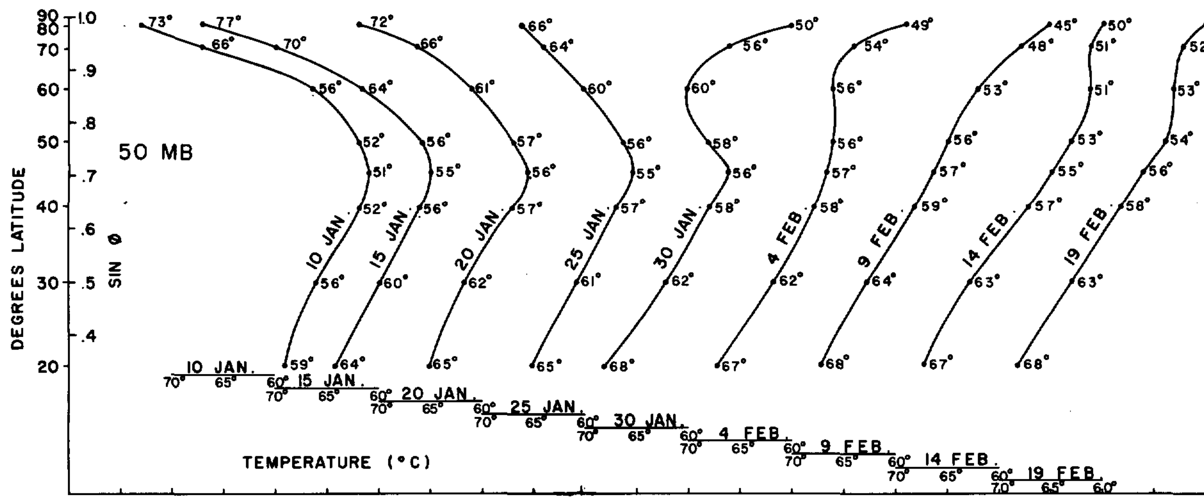

FIGURE 1.—Zonal mean temperatures plotted as a function of sine latitude (ϕ) for 50 mb. Abscissa scale is shifted 10°C to the right for each 5-day interval. Numerical values of (negative) zonal mean temperatures are given at each point to the right of the curve.

time periods. Their results indicate a mean *rising* motion over the polar cap during the sudden warming of 1957. Murgatroyd and Singleton (1961) inferred the existence of the stratospheric mean cell from heat balance considerations, but neglected the effect of eddy heat flux. Their results indicated that a *direct* cell is present in the polar night stratosphere.

In this study, the characteristics of the mean cell will be inferred from the heat balance in preference to the other methods. This choice was motivated by the desire to understand the mechanisms acting to produce the observed rises in the zonal mean temperature during the breakdown period. This calculation will cover periods before, during, and after the polar night vortex breakdown of January 1958. All calculations are performed daily from January 10 to February 19 on a latitude-longitude grid whose southern boundary is 50° N. Selection of this case may provide answers for several questions: the sense and magnitude of the mean cell; the thermodynamic explanation for the large temperature increases during the sudden warming; and the time variability of the mean cell throughout the vortex breakdown period.

2. BASIC DEVELOPMENT

As noted above, in this study particular interest is directed toward determining the heating mechanisms responsible for determining the warming of the polar cap during the breakdown period. For this reason, the approach employed here differs from those employed by the investigators mentioned in the previous section.

Consider the first law of thermodynamics in the form

$$H=c_p\frac{dT}{dt}-\alpha\omega \tag{1}$$

where H is the diabatic heating rate, c_p the specific heat of air at constant pressure, T the temperature, α the specific volume, and ω is the substantial derivative of pressure (dp/dt). By performing an Eulerian expansion of dT/dt and making use of the continuity equation, (1) becomes

$$\frac{\partial T}{\partial t}=\frac{H}{c_p}-\nabla\cdot T\mathbf{V}_2-\frac{\partial}{\partial p}\,\omega T+\frac{\alpha\omega}{c_p}. \tag{2}$$

Now let "$\sim$" denote an area average and "*" represent a point deviation from the area average. Averaging equation (2) over the polar cap north of an arbitrary latitude ϕ_s and employing the divergence theorem yields

$$\frac{\partial\tilde{T}}{\partial t}=\frac{\tilde{H}}{c_p}+\frac{1}{A}\oint_{\phi_s} vTa\cos\phi_s d\lambda-\frac{\partial}{\partial p}\,\tilde{\omega}\tilde{T}-\frac{\partial}{\partial p}\,\widetilde{(\omega^*T^*)}+\frac{\tilde{\omega}\tilde{\alpha}}{c_p}+\frac{\widetilde{\omega^*\alpha^*}}{c_p} \tag{3}$$

where a is the radius of the earth and A the area of the polar cap bounded by ϕ_s. Now, by expanding the $\frac{\partial}{\partial p}\tilde{\omega}\tilde{T}$ term, introducing the area-averaged continuity equation, and noting that $\frac{\alpha}{c_p}=\frac{\kappa T}{p}$ (where $\kappa=.2857$), one obtains

$$\frac{\partial\tilde{T}}{\partial t}=\frac{\tilde{H}}{c_p}+\frac{1}{A}\oint_{\phi_s} vTa\cos\phi_s d\lambda+\tilde{\omega}\left(\frac{\tilde{\alpha}}{c_p}-\frac{\partial\tilde{T}}{\partial p}\right)+\tilde{T}\widetilde{\nabla\cdot\mathbf{V}_2}+\left(\frac{\kappa}{p}-\frac{\partial}{\partial p}\right)\widetilde{\omega^*T^*}. \tag{4}$$

Finally, introducing the zonal averaging operator $(\ )=(\overline{\qquad})+(\ )'$ and employing the divergence theorem yields

$$\frac{\partial\tilde{T}}{\partial t}=\frac{\tilde{H}}{c_p}+\frac{1}{A}\oint_{\phi_s} v'T'a\cos\phi_s d\lambda+\tilde{\omega}\left(\frac{\tilde{\alpha}}{c_p}-\frac{\partial\tilde{T}}{\partial p}\right)+\frac{(\overline{T}(\phi_s)-\tilde{T})}{A}\oint_{\phi_s} va\cos\phi_s d\lambda+\left(\frac{\kappa}{p}-\frac{\partial}{\partial p}\right)\widetilde{\omega^*T^*}. \tag{5}$$

Equation (5) shows that mean heating over an area can occur through diabatic heating, horizontal eddy heat flux through the outer boundary, adiabatic compression, mean inflow when the boundary temperature is warmer than the interior, and by convergence of eddy heat flux in the vertical. Solving equation (5) for $\tilde{\omega}$ and expressing the integral terms in computational form gives

$$\tilde{\omega}=\frac{1}{\left(\frac{\tilde{\alpha}}{c_p}-\frac{\partial\tilde{T}}{\partial p}\right)}\left[-\frac{\tilde{H}}{c_p}+\frac{\partial\tilde{T}}{\partial t}-\frac{\cos\phi_s}{a(1-\sin\phi_s)}(\overline{T}(\phi_s)-\tilde{T})\overline{v}(\phi_s)\right.$$
$$\left.-\left(\frac{\kappa}{p}-\frac{\partial}{\partial p}\right)\widetilde{\omega^*T^*}-\frac{\cos\phi_s}{a(1-\sin\phi_s)}\overline{v'T'}(\phi_s)\right]. \quad (6)$$

The above equation is in a form that can be evaluated from the basic meteorological data.

3. COMPUTATIONAL RESULTS

The first term in equation (6) is somewhat difficult to evaluate directly, since it demands a knowledge of the mean diabatic heating in the polar night stratosphere. Works by Ohring (1958) and Davis (1963) suggest a net radiative cooling of 1°C per day for the lower polar stratosphere during the winter season while Kennedy (1964) obtains a somewhat lower value. For convenience, however, a value of 1°C day^{-1} will be used for the first term in equation (6). Since this term contains a probable uncertainty of about .5° day^{-1}, it may represent a source of error for the calculation. However, in view of the form of equation (6) the effect of error in this term on the computed $\tilde{\omega}$ is quite clear.

The second term in equation (6) was evaluated by first plotting successive charts of zonal mean temperature with respect to sin ϕ (fig. 1). Then, a graphical determination of the mean temperature change over the area of interest for 5-day increments was performed.

In equation (6) the third term presents some difficulty since it involves $\overline{v}$, a part of the mean cell. However, this term is generally quite small and can be included in several ways. It can either be independently estimated from the momentum budget or it can be determined iteratively by initially evaluating equation (6) without the $\overline{v}(\phi_s)$ term, then estimating $\overline{v}(\phi_s)$ from the area-averaged continuity equation in the form

$$\frac{\partial\tilde{\omega}}{\partial p}=\frac{1}{A}\oint_{\phi_s} va\cos\phi_s d\lambda=\frac{\overline{v}(\phi_s)\cos\phi_s}{a(1-\sin\phi_s)}. \quad (7)$$

Calculations of the third term in equation (6) by the above method indicate that its contribution is extremely small (less than 0.1° day^{-1}) and can be readily neglected since this is well within the uncertainty contained in the radiation term.

The fourth term in equation (6) can be evaluated from point calculations of the ω field. Evaluation of this term from the synoptic scale vertical motion fields (Mahlman, 1966, 1967) indicate that its contribution is extremely small in the stratosphere (less than 0.1° day^{-1}). Consequently, the term will be neglected. However, one cannot dismiss the possibility that the term may contribute more significantly at smaller motion scales.

The evaluation of the fifth term (eddy heat flux) was accomplished by a careful tabulation of wind and temperature at the grid points for successive latitudes. Contrary to Murgatroyd and Singleton (1961), the evaluation shows this term to be extremely important in the heat budget. This result also was inferred indirectly by Reed, Wolfe, and Nishimoto (1963).

It should be noted that equation (6) in its present form only gives the mean vertical motion north of a given latitude ϕ_s, which can be 50° N., 60° N., or 70° N. in this study. One can obtain values for the intermediate regions, 50°→60° N. and 60°→70° N., by evaluating expressions of the form

$$A^*(\phi_s\to\phi)\tilde{\omega}(\phi_s\to\phi)+A^*(\phi\to 90°)\tilde{\omega}(\phi\to 90°)$$
$$=A^*(\phi_s\to 90°)\tilde{\omega}(\phi_s\to 90°) \quad (8)$$

where A^* represents the area enclosed between the latitudes indicated in parentheses.

Figure 2 gives the results of computations of the mean cell obtained from the above scheme for periods before, during, and after the polar vortex breakdown. For clarity, the $\tilde{\omega}$ values were converted to vertical motions ($\tilde{w}$) in kilometers day $^{-1}$ using the usual approximate conversion with the hydrostatic equation. This figure shows that a well-pronounced mean *ascent* is present over the polar cap during all three calculation periods even though the mean properties of the polar vortex change drastically between January 10 and February 19. However, the apparent intensity of this cell is *greatest* during the breakdown period.

This type of mean cell agrees in general with the dynamical calculations by previous investigators, but disagrees with the circulation deduced from measured transports of trace substances in the stratosphere. It also disagrees with Murgatroyd and Singleton's results (1961), which neglect the effect of eddy heat transport.

4. HEATING MECHANISMS DURING THE SUDDEN WARMING

Some controversy has existed in the literature concerning the physical mechanisms that act to produce the dramatic temperature increase over the polar cap during the sudden warming period. Equation (5) shows the heating mechanisms that can act to produce the observed warming.

In the past, the most popular hypothesis has been that the warming is produced by rapid adiabatic descent over the Pole during the breakdown period. However, figure 2 shows that the mean cell is producing *rising* motion over the polar cap during the warming period. Thus, according to this result, the adiabatic descent mechanism does not provide a plausible explanation for the heating during the sudden warming phenomenon. On the other hand, descending motion is possibly quite important in explaining very large temperature increases occurring in limited areas.

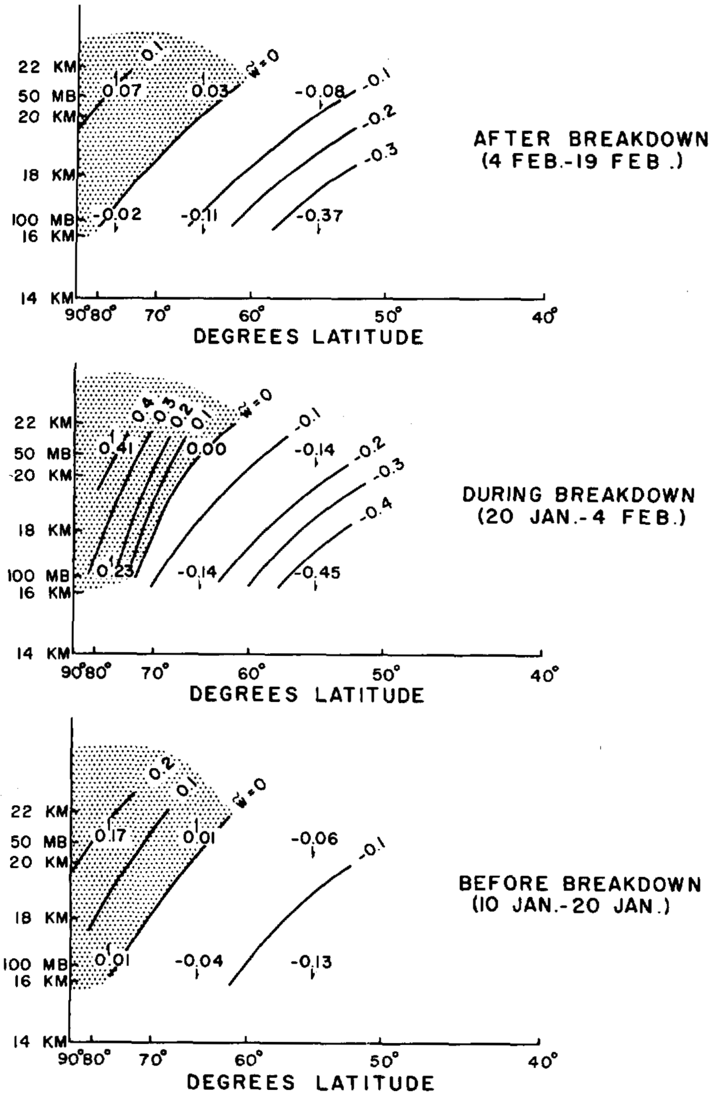

FIGURE 2.—Area-averaged vertical motion (w) in kilometers day^{-1} computed from equations (6) and (8) for indicated periods before, during, and after the polar vortex breakdown of January–February 1958. Hatching denotes area of rising motion.

TABLE 1.—*Contribution of dominant terms in equation (5) for heat balance of the polar cap in the stratosphere (units: deg day^{-1}). Computation is separated into periods before, during, and after the polar vortex breakdown.*

	Observed warming	Radiation (estimated)	Mean cell	Eddy flux
100 mb	Before breakdown Jan. 10–20			
N. of 50° N	0.0 deg day^{-1}	−1	+0.3	+0.7
N. of 60° N	+0.1	−1	−0.3	+1.4
N. of 70° N	+0.2	−1	0.0	+1.2
50 mb				
N. of 50° N	−0.4	−1	−0.4	+1.0
N. of 60° N	−0.2	−1	−1.0	+1.8
N. of 70° N	−0.3	−1	−1.5	+2.2
100 mb	During breakdown Jan. 20–Feb. 4			
N. of 50° N	+0.4	−1	+1.2	+0.2
N. of 60° N	+0.8	−1	−1.1	+2.9
N. of 70° N	+1.1	−1	−2.2	+4.3
50 mb				
N. of 50° N	+0.7	−1	−0.1	+1.8
N. of 60° N	+1.0	−1	−1.7	+3.7
N. of 70° N	+1.3	−1	−3.9	+6.2
100 mb	After breakdown Feb. 4–19			
N. of 50° N	+0.1	−1	+1.6	−0.5
N. of 60° N	+0.1	−1	+0.4	+0.7
N. of 70° N	0.0	−1	+0.4	+0.6
50 mb				
N. of 50° N	+0.1	−1	+0.3	+0.8
N. of 60° N	0.0	−1	−0.2	+1.2
N. of 70° N	−0.2	−1	−0.4	+1.2

The above arguments point to the horizontal eddy flux of heat as the controlling mechanism for the observed mean temperature increase. Table 1 contains tabulated values of the dominant terms in equation (5) for periods before, during, and after the sudden warming at 100 and 50 mb for the regions north of 50° N., 60° N., and 70° N., respectively. This table shows that a pronounced change in the area mean temperature is occurring during the breakdown period. Also, in general, the horizontal eddy heat flux term is importing considerably *more* heat into the polar cap than is actually reflected in the observed temperature increases. Note further that the horizontal eddy heat flux into high latitudes is much *larger* during the breakdown period than in the prior or subsequent periods.

The effect of the eddy heat flux on the observed area-mean temperature increases may be readily seen in figure 3. This figure is a plot of predicted temperature increases calculated from the eddy heat flux against the observed temperature increases calculated over 5-day periods. It is clear from this figure that observed temperature increases in the polar cap are highly related to the eddy heat flux into it during this period. Figure 3 also shows that in virtually all cases at 60° N. and 70° N. the computed eddy heat flux into the region is *greater* than the observed mean warming within it. This result is another way of showing that the mean cell over the Pole must be *rising* to compensate for this large eddy heat flux. Consequently, it can be concluded on the basis of these computations that a pronounced increase in the horizontal eddy heat flux during this period is primarily responsible for the observed zonal mean temperature increases associated with the polar vortex breakdown. It should be noted that this only pinpoints the predominant physical process producing the warming, but says nothing about the mechanisms producing the breakdown itself.

To arrive at a clearer indication of the significance of the above relationship between observed warming and

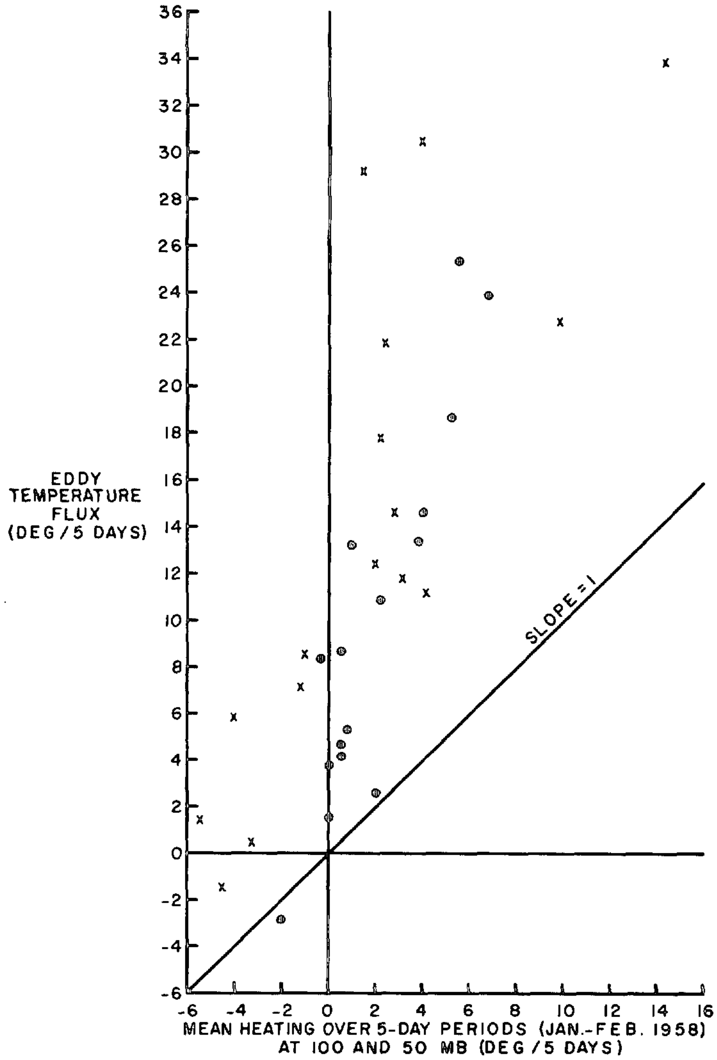

FIGURE 3.—Plot of horizontal eddy temperature flux against observed area-mean temperature increases. Values are computed over 5-day periods from Jan. 10 to Feb. 19, 1958, at 100 mb and 50 mb and at 60° N. and 70° N. x's denote 50-mb data and closed circles are 100-mb values.

eddy heat flux, correlation coefficients were computed from the data given in figure 3. For 50 mb, 60° N. and 70° N., over the time interval of January 10 to February 19 the correlation coefficient between these two quantities was +0.81. For 100 mb, 60° N. and 70° N., the value was +0.86. In view of the almost complete independence between computations of the eddy heat flux and observed warming, these correlation coefficients are highly significant. However, if the 100- and 50-mb data of figure 3 are combined, the correlation coefficient drops to +.50. This is still statistically significant, but strongly suggests that the warming response to the eddy heat flux is somewhat different between the two levels.

5. MEAN CELL WITH RESPECT TO A CURVILINEAR COORDINATE SYSTEM

The above analysis has corroborated the contention of the previous authors who argued that the mean meridional circulation is *indirect* prior to the polar vortex breakdown. This type of mean cell has the characteristic of transporting air (also ozone and radioactivity) upward and away from the polar regions. Consequently, the mean cell acts in a sense opposite to the observed debris transports. This may not strictly be the case, however, when one considers the results obtained from geophysical model experiments at the University of Chicago Hydrodynamics Laboratory (Riehl and Fultz, 1957). These experiments demonstrated for a three-wave laboratory case that, if one averages the vertical motion with respect to latitude, an indirect cell is present in the vicinity of the midlatitude jet stream. On the other hand, if one averages with respect to the jet stream itself, a well-pronounced *direct* cell results. Although this seemingly contradictory phenomenon has never been explicitly documented in the actual atmosphere, there remains a definite possibility of its existence. Krishnamurti (1961) performed a computation of this nature on the circulation around the subtropical jet stream. His results indicated that this cell was in the same sense as the Hadley cell present in that region.

In order to examine this possibility, the height contour of maximum circulation intensity was noted on the 50-mb surface. Then by interpolating from hemispheric analyses of vertical motion computed from equation (1) (Mahlman, 1966), values were tabulated at distances of +10°, +5°, 0°, −5°, and −10° latitude on a line normal to this chosen height contour. This process was repeated at intervals along this contour (approximately 15 equally spaced grid points) for the period Jan. 10–27, 1958. No attempt was made to extend the calculation past January 27 because the polar night jet stream ceased to exist after this date. The process was repeated at 100 mb, utilizing the same contour employed at 50 mb. By using the same contour at both levels, continuity with height was assured. The mean vertical motion was then calculated for each day at the given distances +10°, +5°, 0°, −5°, −10° latitude from the selected height contour or jet axis. These values were then composited separately at each level over the entire period January 10–27. Figure 4 shows that, according to these measurements, the circulation is thermodynamically *direct* with respect to this curvilinear coordinate (circulation latitude) system, a result *opposite* to that obtained by averaging with respect to geographical latitude. There is an indication that the orientation of the mean vertical motion field in figure 4 is slanted similarly to the latitudinally averaged cell in figure 2 but of opposite sign.

It should be noted, however, that extreme caution should be exercised before extrapolating this result to periods either before or after the chosen period of January 10–27. In the period before this, the asymmetry of the vortex may not have been sufficient to produce such a pronounced difference between the two types of coordinates. After January 27 the polar night jet stream ceases to exist as a continuous circumpolar phenomenon, and the intensity of the ω fields is considerably weakened. Consequently,

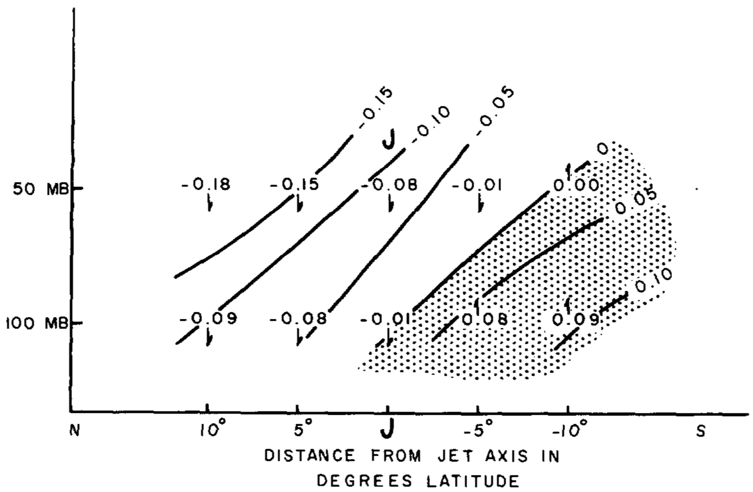

FIGURE 4.—Time composite of mean vertical motion (kilometers day^{-1}) with respect to the coordinate system oriented along a line of maximum circulation intensity at 50 mb. The composite is for the period Jan. 10–27, 1958. Hatching denotes area of rising motion.

after the warming it is extremely difficult, if not impossible, to construct a well-defined curvilinear coordinate system. The concept thus may become meaningless in this case. This result shows that stratospheric mean cells may depend to a large degree upon the choice of the reference frame used in the analysis.

6. SUMMARY

A computation of the stratospheric mean meridional circulation for periods before, during, and after the major polar vortex breakdown of January–February 1958 was performed by using a heat balance method. The results showed that the mean cell produces rising motion over the polar cap during the sudden warming period, and consequently cannot be invoked as a thermodynamic explanation of the sudden warming phenomenon. Examination of the various terms in the mean cell computation indicated that quasi-horizontal eddy heat flux provides the necessary warming mechanism.

As a supplement to the mean cell computation, a calculation was made of the mean vertical motion with respect to a curvilinear coordinate system oriented along a line of maximum circulation intensity. This demonstrated that, for the period before and during the vortex breakdown, the mean circulation is *direct* when measured relative to such a coordinate system.

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NOTICE TO CONTRIBUTORS

February 9, 1970, marks the 100th anniversary of national weather services in the United States. Since the history of the *Monthly Weather Review* is nearly coincident with the history of the weather service itself, it seems fitting that contributors to the *Review* should have an opportunity to observe the United States Weather Services Centennial (U.S. WESCENT), scheduled for 1970.

Accordingly, authors who wish to do so are encouraged to introduce into their planned research contributions, offered during the next 6 or 8 months, the historical theme of the Centennial. Citing the work of American meteorologists as it has found expression either within or through the national weather services would seem to be a natural way of commemorating those services. It is not intended that all nor even most of the articles appearing in the *Review* during 1970 allude to the Centennial. Authors should consult their own interests, material, and sources to determine whether such a reference would be appropriate and effective.